Kaonic nuclei excited by the in-flight (K^-,n) reaction

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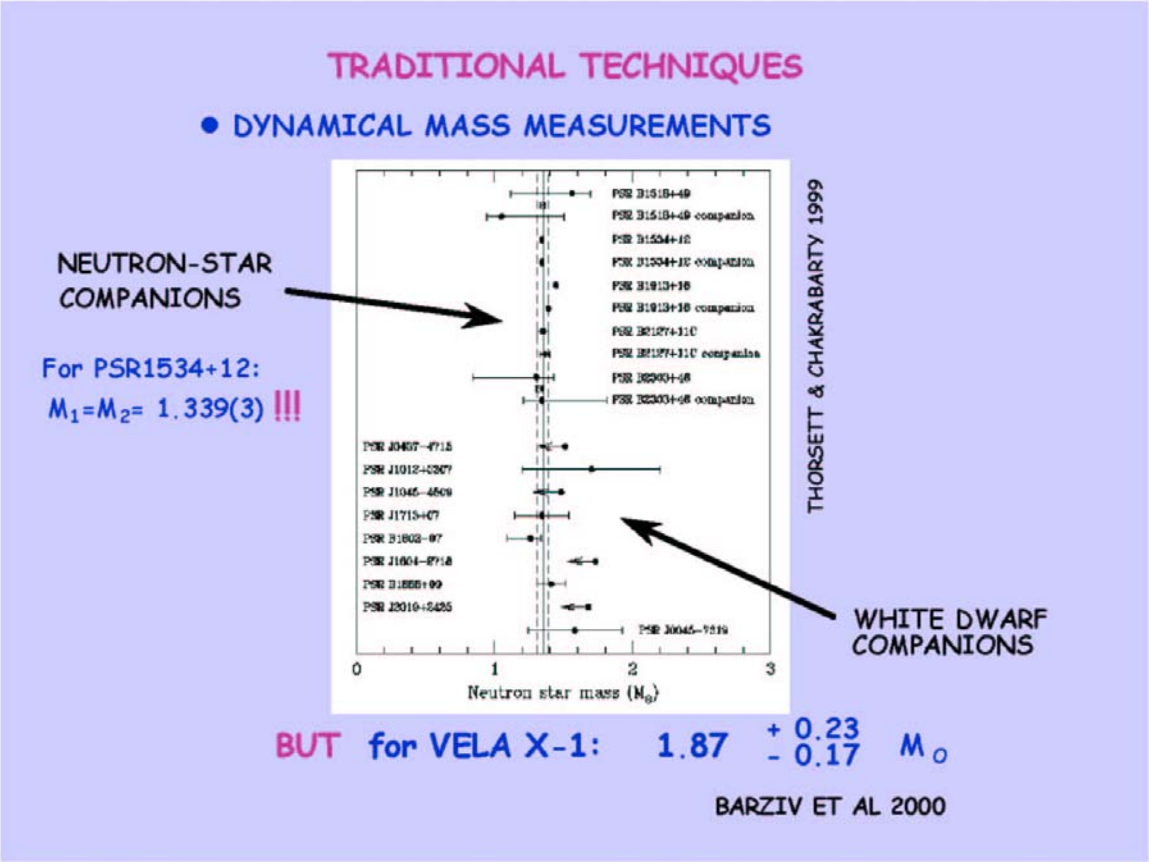
Neutron Stars



No Strangeness
~2 Solar mass

Strangeness
~1.5 Solar mass

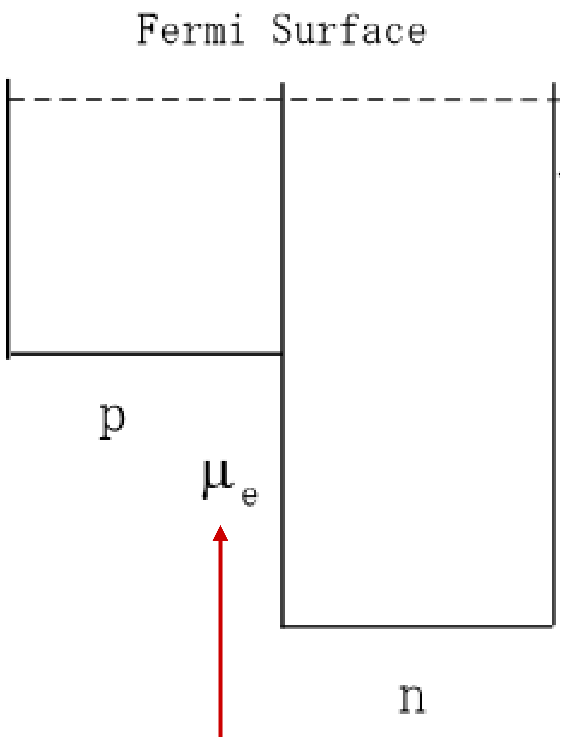
ρ ~ 3-5 ρ_0
Nuclear matter
with hyperons

Kaon condensation
K-nucleus interaction

M~1.4 solar mass

Talk by I. Bombaci

Hyperons in Neutrons Stars



Electron Chemical potential
Charge neutrality

Negative charged particle

Σ^{-} repulsive

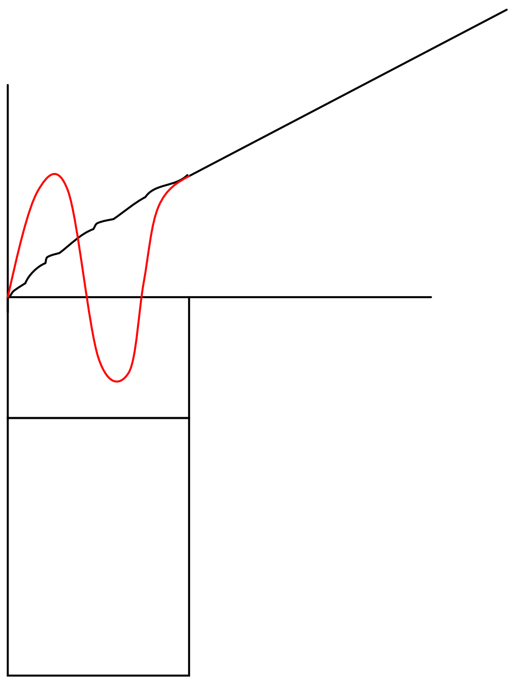
Kaon condensation
K-N int

K-nucleus interaction

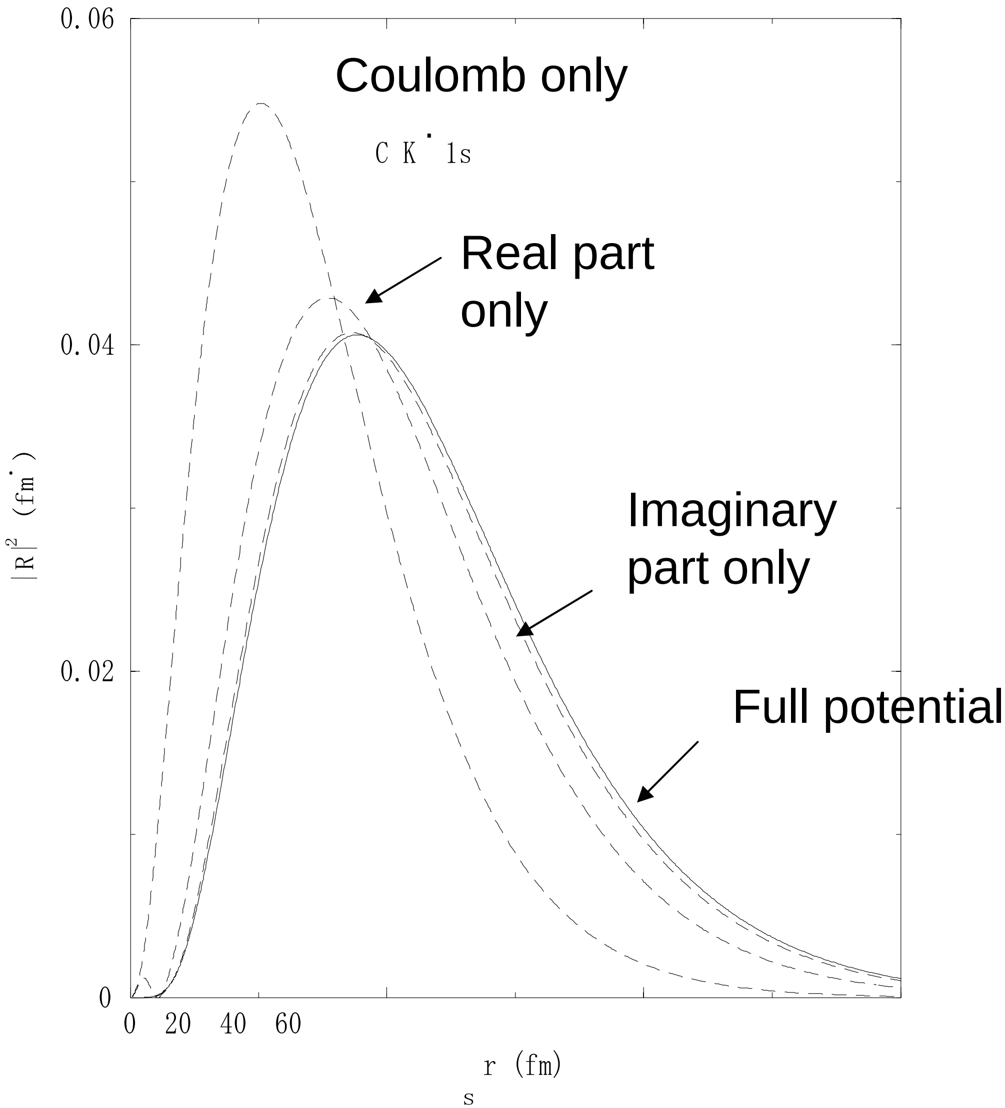
- Atomic X ray data suggest two solutions (Batty, Freedman, Gal, PR287,385'97)
  - deep ~180 MeV K-con (m_K~2.5 ρ U)
  - shalow ~80 MeV no K-con
  - Phase shift of K- w.f. at the nuclear surface
- Heavy Ion reaction attractive
  - KAOS talk by V. Koch
- Λ(1405)
  - KN bound state
  - K^- p X ray data
    - repulsive (bound state) strongly attractive

Atomic X ray data

Konic atom
Wave function



Nodes
Imaginary part



Dispute in theoretical calculations on the antikaon-nucleus potential

- Shallow potential (40-80 MeV)
  - Chirally motivated models
  - Meson Exchange

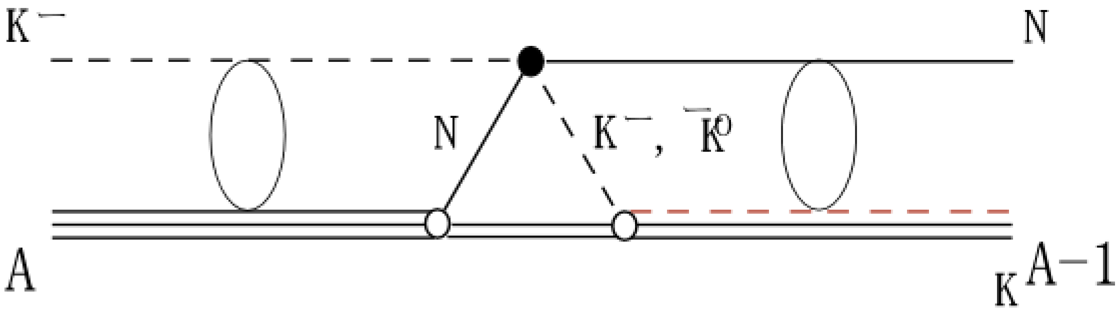
  Gal, Oset, Ramos, Weise, Toki, ……..Many
- Deep potential (~200 MeV)
  - Phenomenological models

  Akaishi, Yamazaki,

Kaonic Nuclei

- Experimental information so far $\rightarrow$ peripheral
- Put a K in the core of a nucleus
  - Kaonic nuclei
- Direct information on the K-nucleus Interaction
- Can we observe the states?
  - $BE_{1s} \sim 3/2\ h\nu - U$
  - Width could be as narrow as 10-20 MeV
    - For deeply bound states (Waas, Kaiser, Weise, PLB 379,34'96)
    - $\Gamma \sim 100$ MeV at the threshold (BFG, PR287)
  - Cross section reasonably large TK,PRL'99

Production of Kaonic Nuclei by the in-flight (K^-,N) reactions



TK, PRL83,4701, '99

★Virtual Kaon Beam

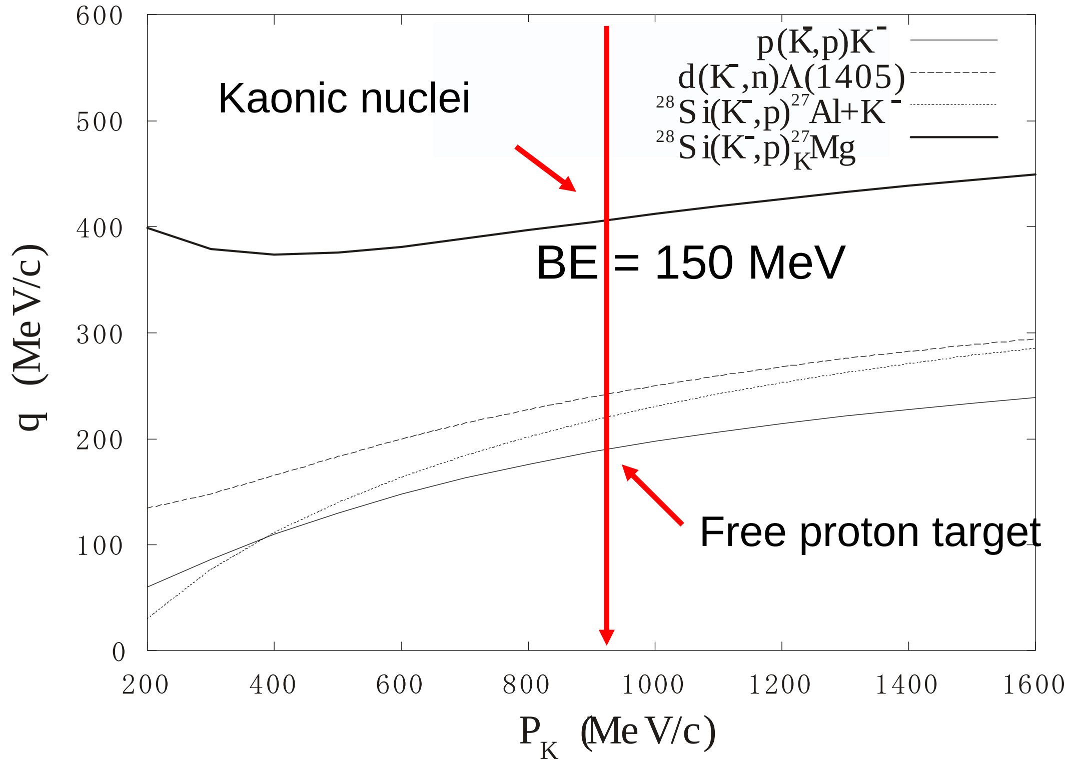
★Background ~ Spreading width

★Highest energy nucleons

Many others;
Yamazaki, Akaishi,
Iwasaki, Nagae

Characteristic of the reaction

- Momentum transfer
  - ~400 MeV/c
  - (π^+, K^+) for hypernuclear production
- Similar Gross structure of spectrum



Cross section

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{L,0^\circ}^{K^- N \to N K^-} N_{\mathrm{eff}} \, .$$

Elementary cross section

$$N_{\mathrm{eff}}^{\mathrm{pw}} = (2J+1)(2j_N+1)(2\ell_K+1) \times \begin{pmatrix} \ell_K & j_N & J \\ 0 & -\frac{1}{2} & \frac{1}{2} \end{pmatrix}^2 F(q) \, .$$

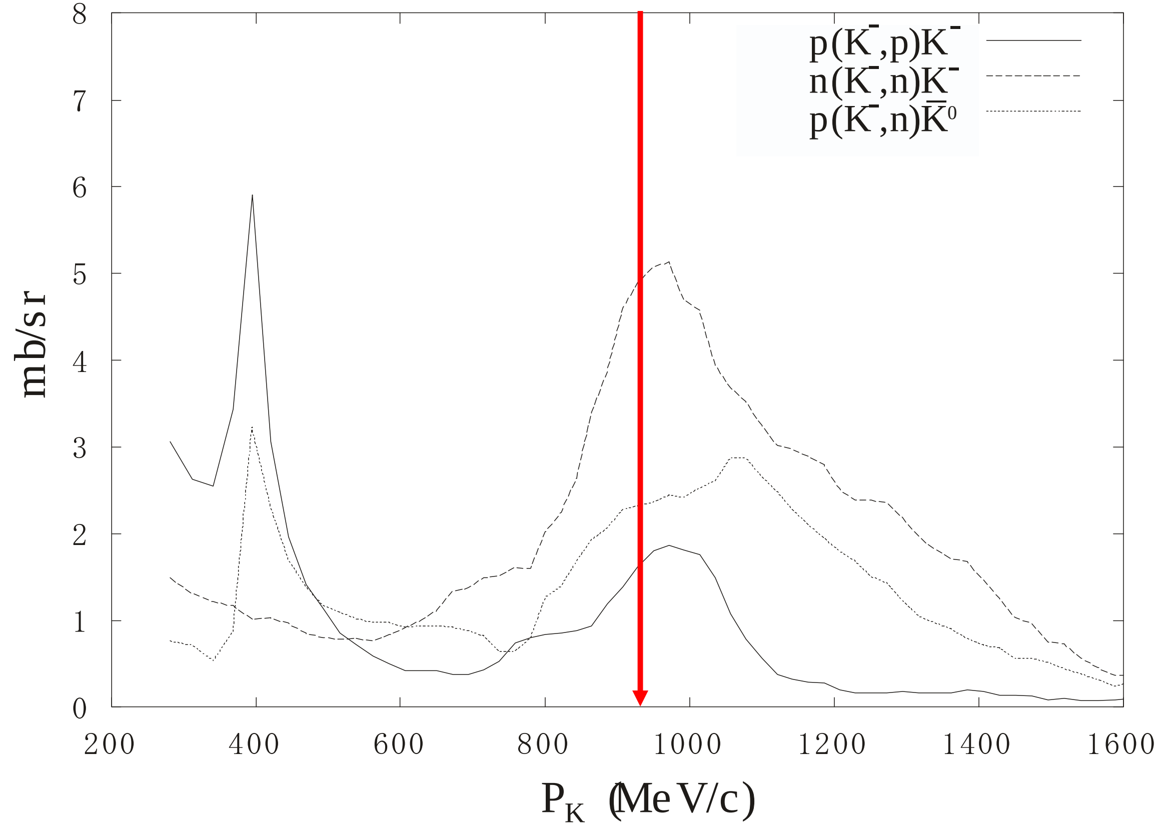
Form factor

Harmonic Oscillator

$$F(q) = \frac{(2Z)^L e^{-Z}}{[(2L+1)!!]^2} \frac{[\Gamma(L+3/2)]^2}{\Gamma(\ell_K+3/2)\Gamma(\ell_N+3/2)}$$

$z / (bq)^2/2$

Elementary cross section

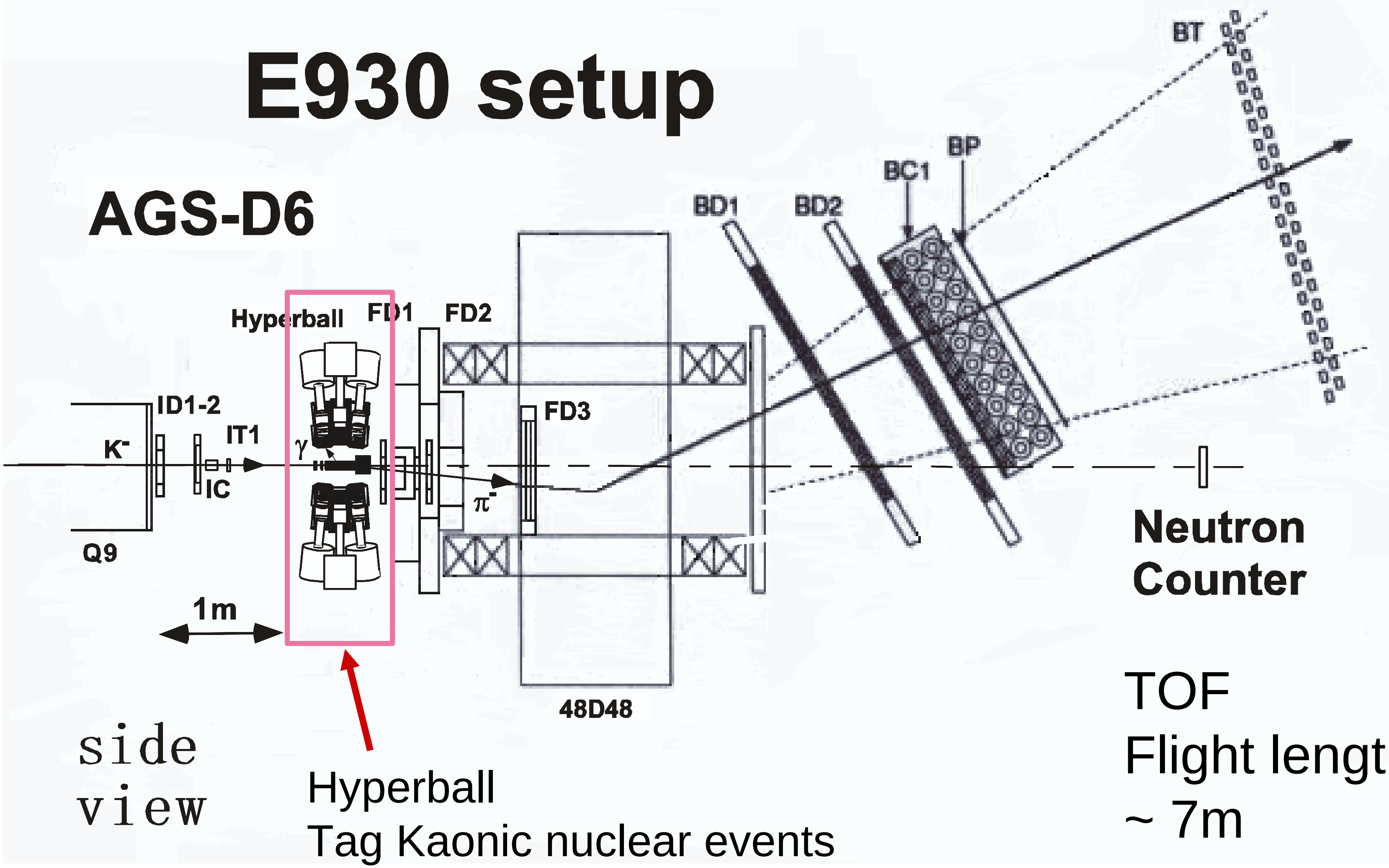


Experiment

- E930 parasite
  - $^{16}O(K^-,\pi^-\gamma)^{16}{}_{\Lambda}O$ (Hyperball)
- P_K = 930 MeV/c ⇨ Best for (K^-,N) reaction too
- Measured neutrons from the $^{16}O(K^-, n)$
- Neutron counters
  - 100cm(W) x 20cm(H) x 20cm(D)
  - 0 degrees
  - 7m from the target
- 4.7 G K^-

Setup of the Experiment

Parasite E930

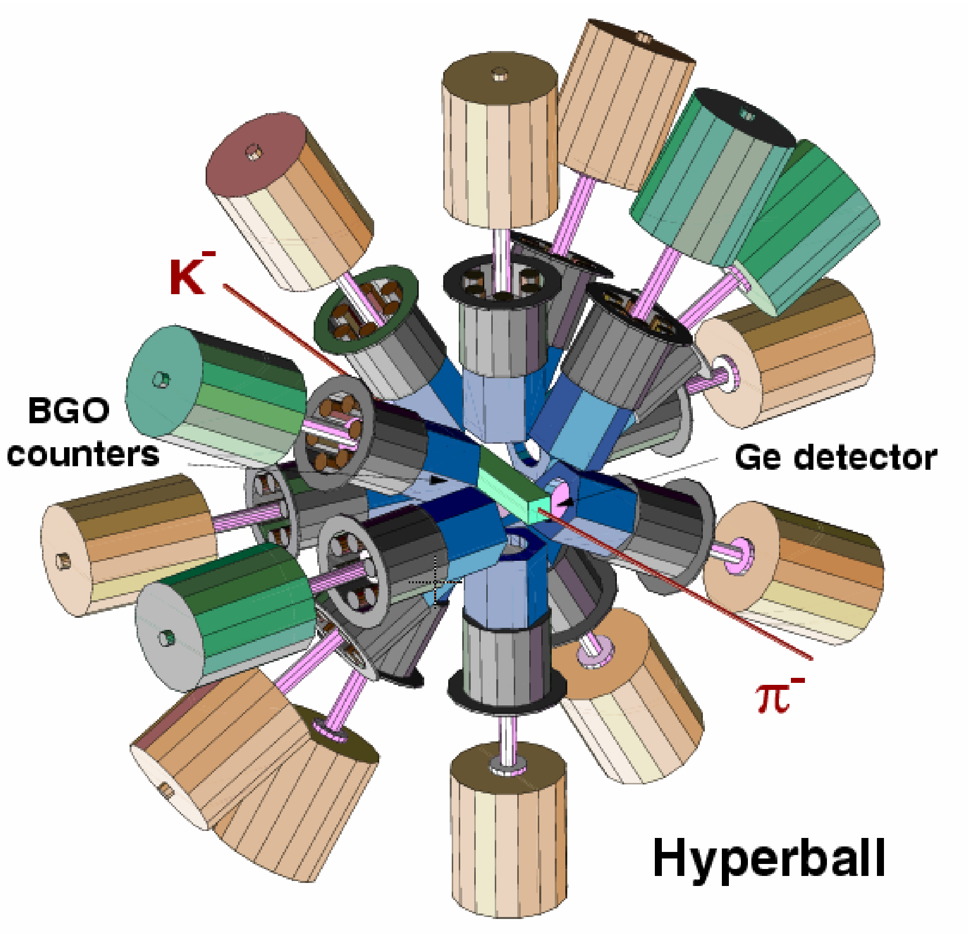


Neutron Counter

Hyperball
Tag Kaonic nuclear events
~0.2 (4π)

TOF
Flight length
~ 7m

Decay Counter (Hyperball)



- solid angle
  ~20% (Ge detector)
- Emax ~ 7 MeV

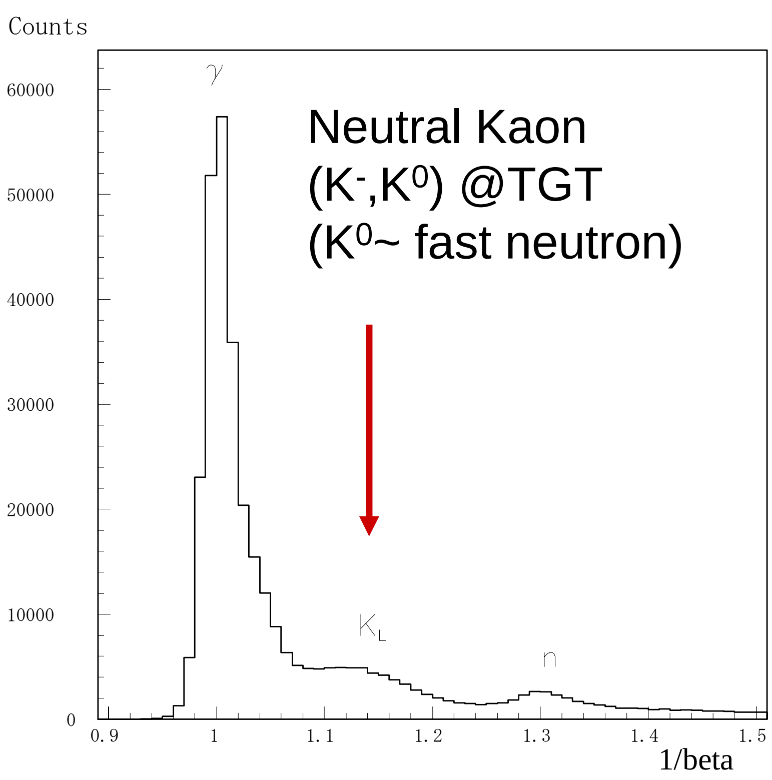
To tag decay products from Kaonic nuclei

↓

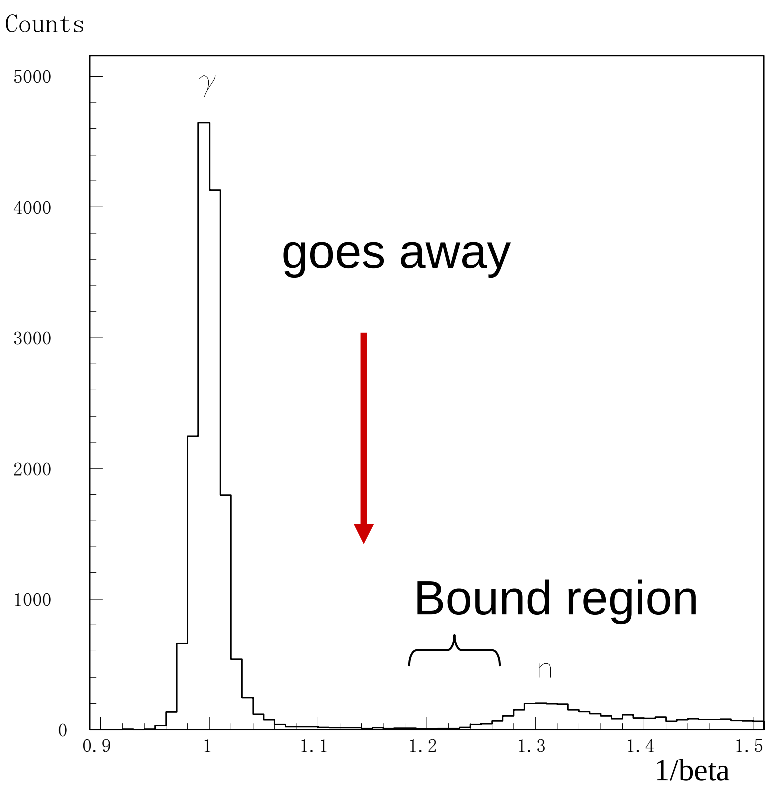
- Kaonic nuclei
  Λ (1405) ! Σ π ! N π π
  or YN production
  ! Charged particles
- Background process
  p(K^-, K^0)n
  K^0 ! fast neutron
  no charged particle
  n ! calibration
- Kaon decay

TOF(1/β) spectra

before

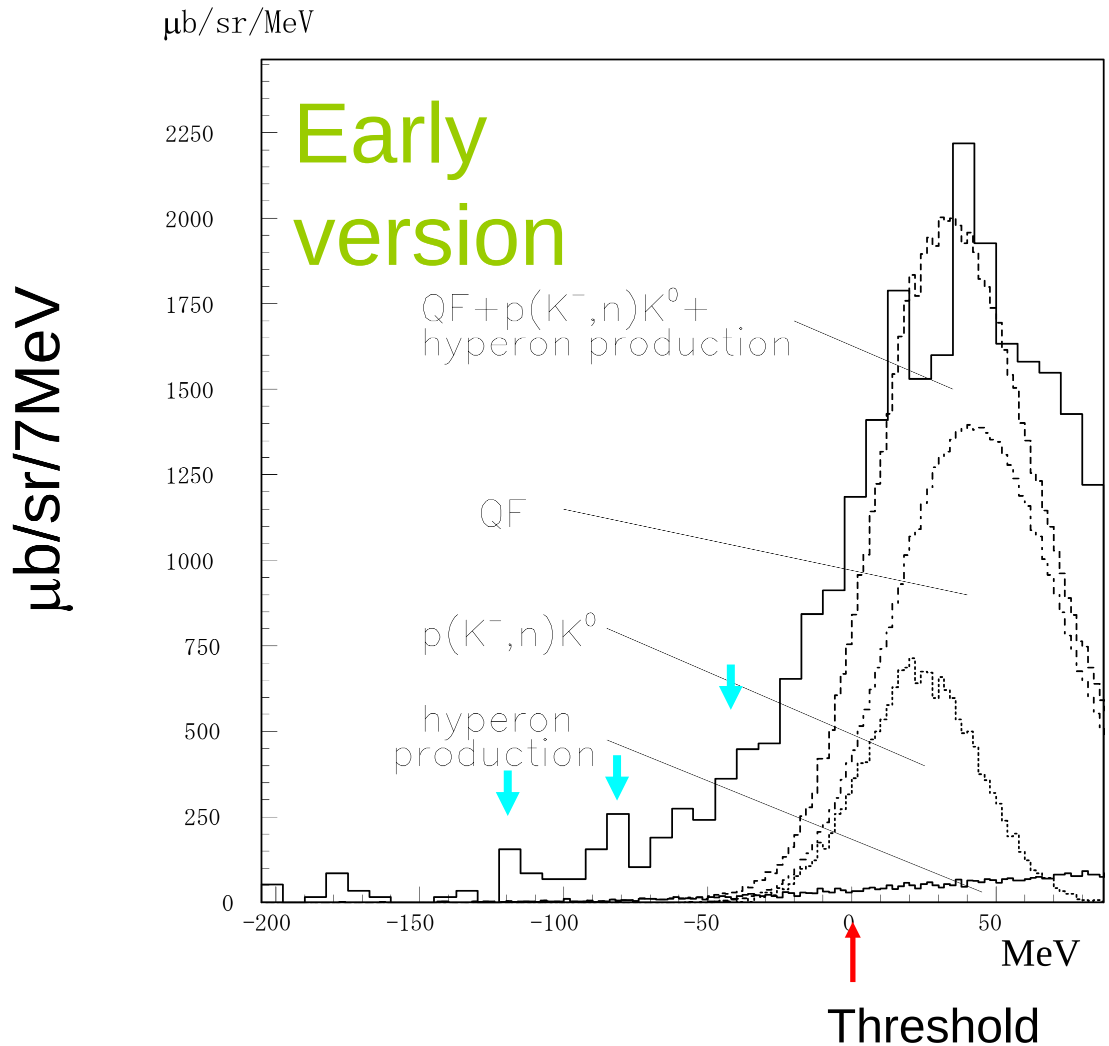


Raw



Hyperball + dE/dX cut

Excitation energy spectrum



- ¢ Strength in bound region
- ¢ Interesting structure althogh

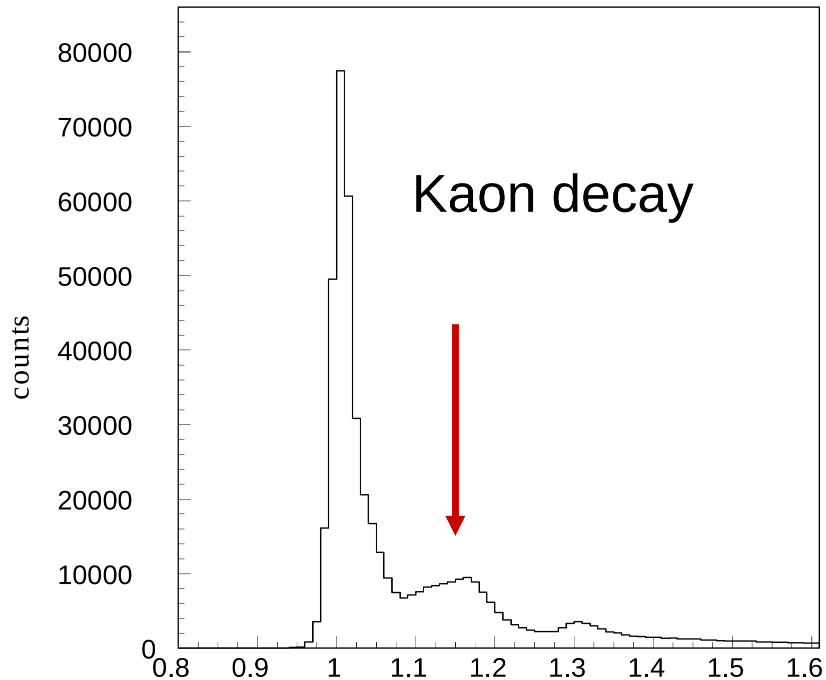
Results were not stable

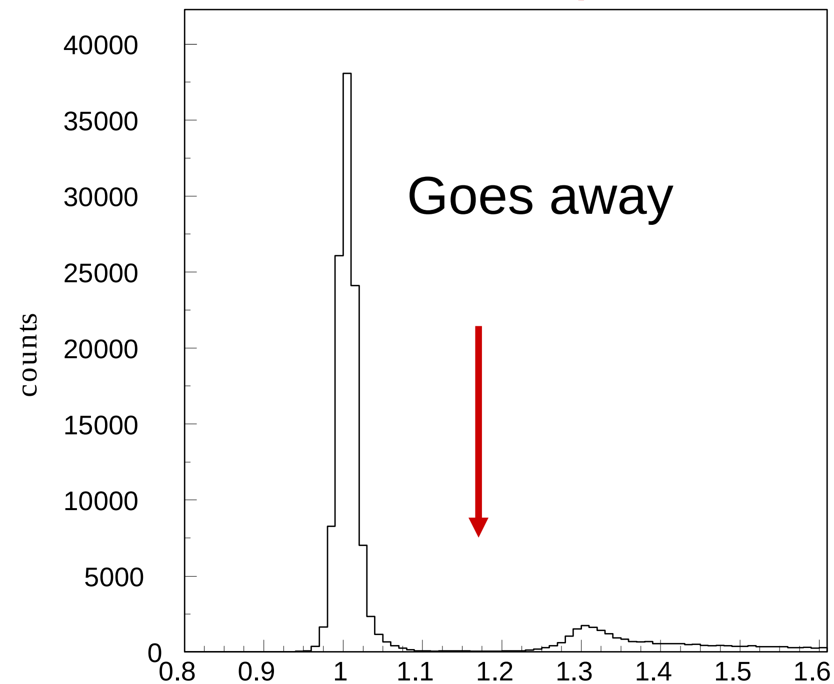
TOF(1/β) spectra

Raw

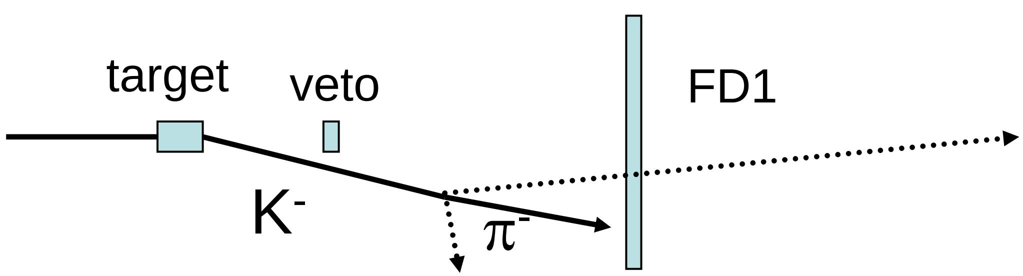
after

No hits in FD1-3
No Ge help



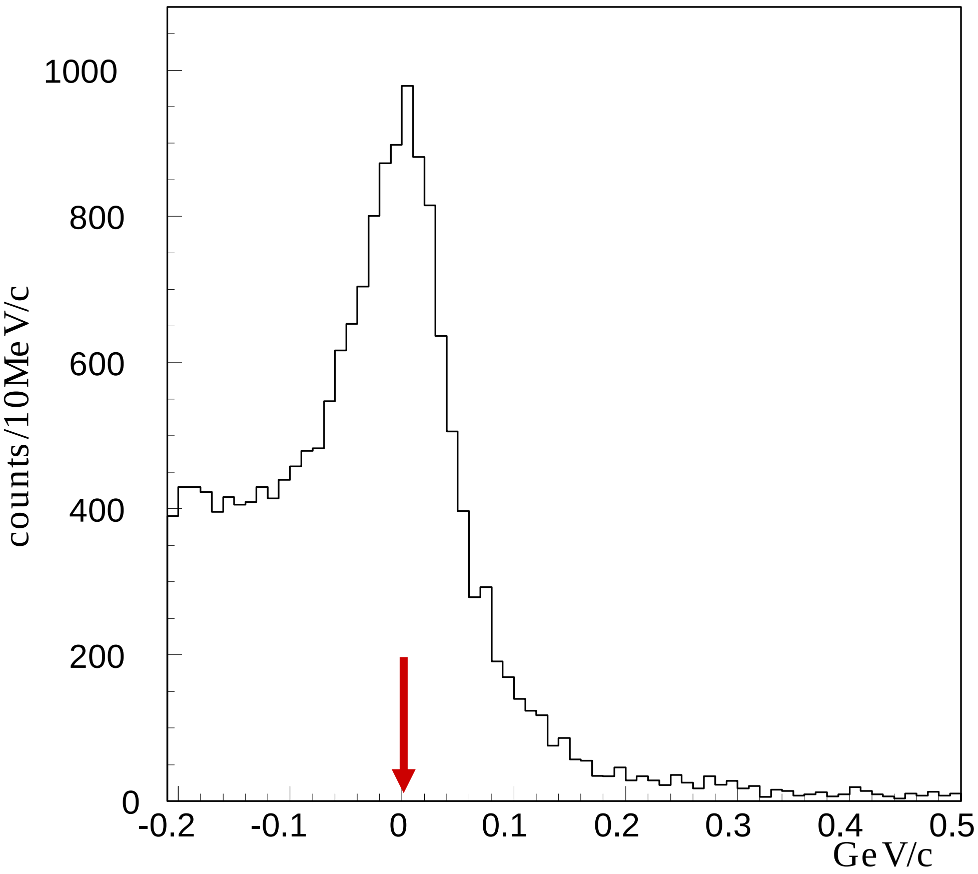


γ from K- ! π^{-} π^{0}



Momentum spectrum

Inclusive (FD cut)



p_n(mes)-p_n(cal)

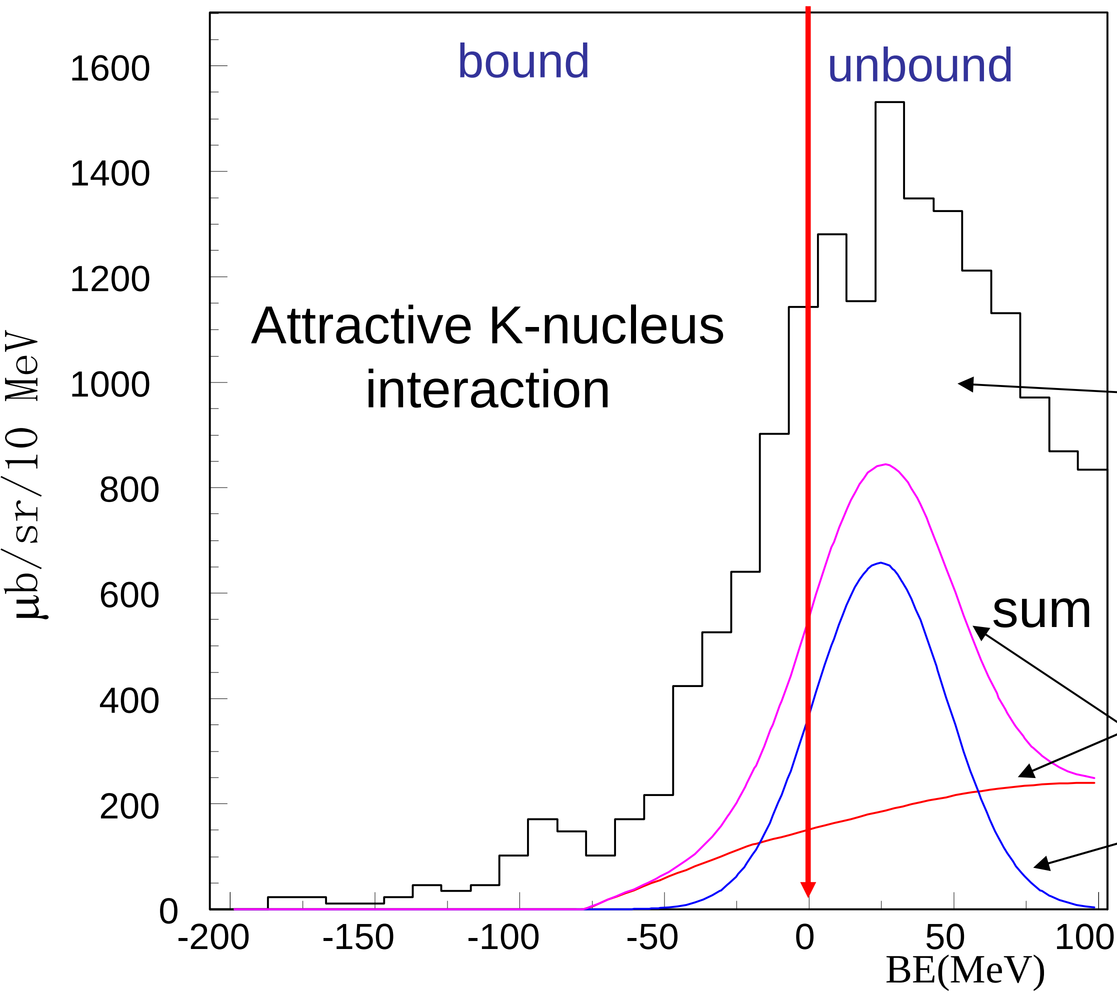
p_n~ 1.2 GeV/c

$p(K^-,n)K^0$

P calibration

Only by TOF

Energy Spectrum (Ge cut)



$^{16}O(K^-,n)$

Hyperon production

$p(K^-, n)K^0$
Resolution (TOF)

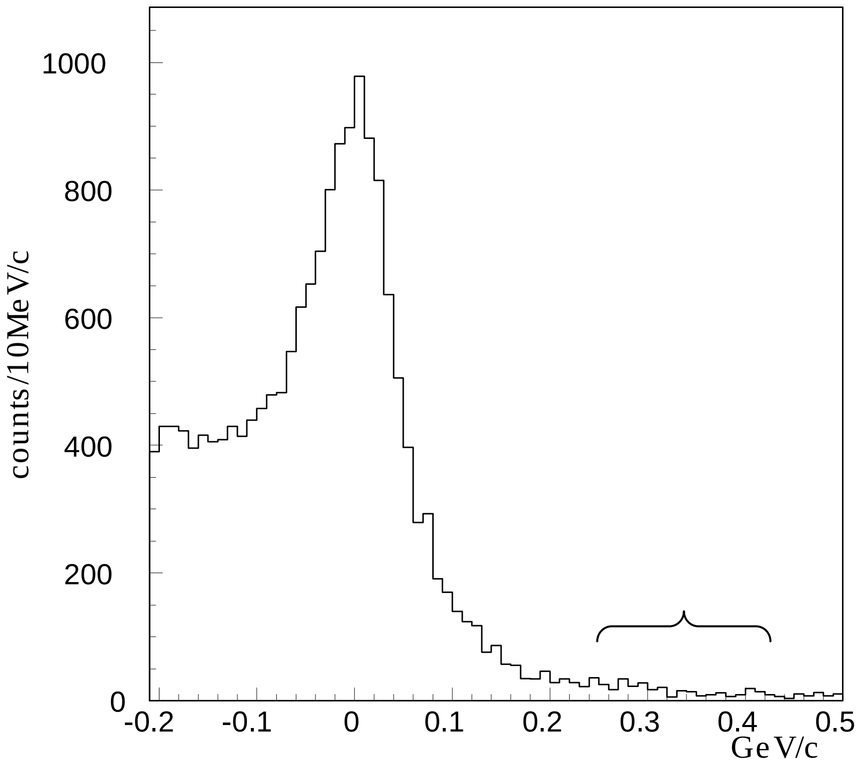
$M(^{15}O+K^-)$

Cross section (Gopal)

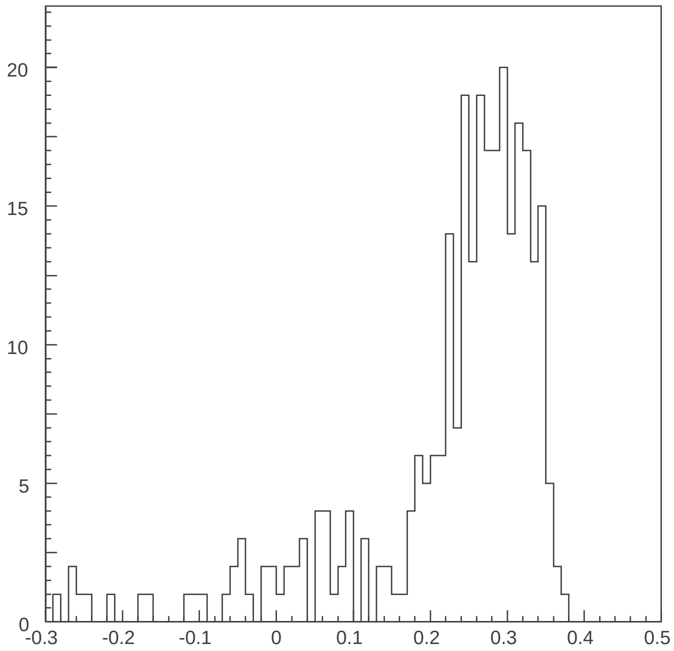
Source of energetic neutron background

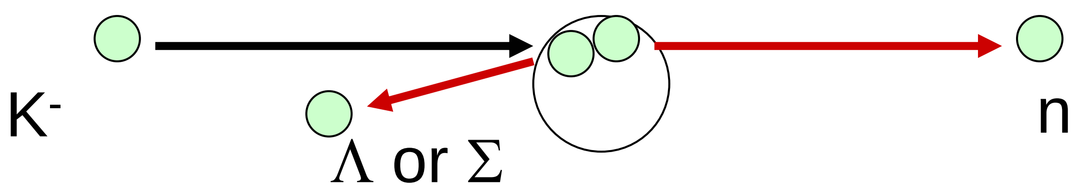
- 2 nucleon absorption
  - K^- NN ! YN   not seen so far
- Hyperon production
  - N(K^-, π)Y where π scattered backwaords
  - Λ (Σ) ! n π n: forward
  - Cross section (Gopal), GEANT
- Production of Λ or Σ hypernuclei
  - Not seen so far

2 nucleon absorption background

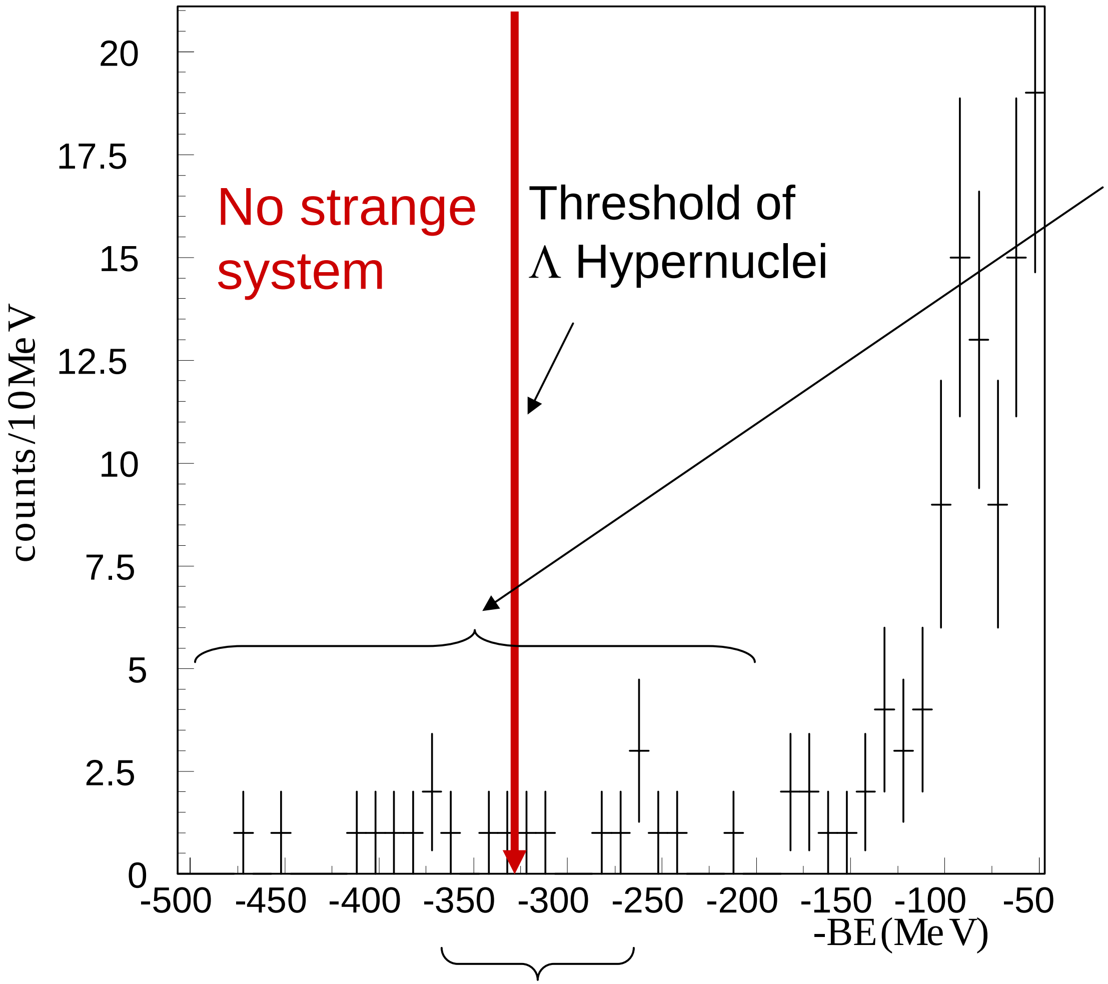


Simulation for the KNN ! YN





Backgrounds

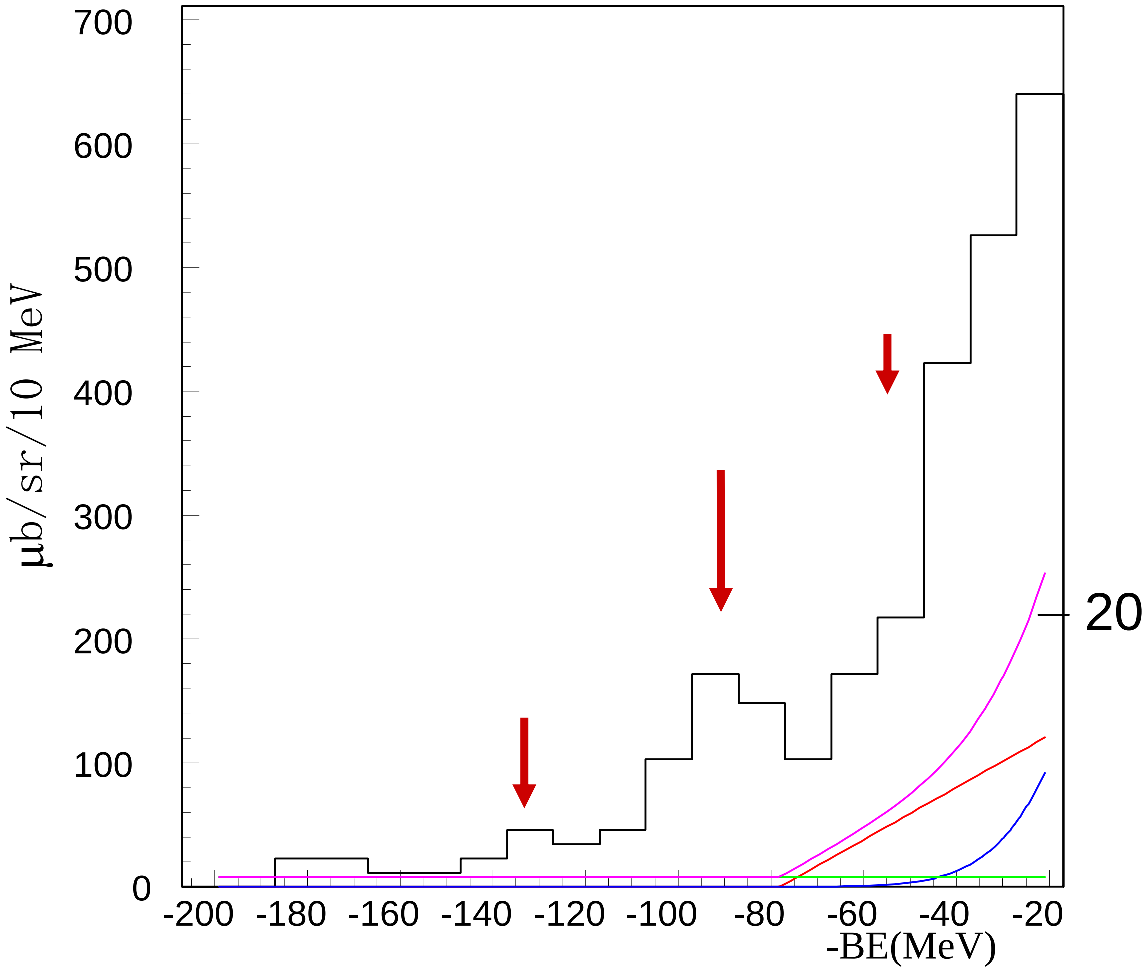


Background
Flat

-BE=200-500 MeV
21 events
0.7 events/10 MeV

2 nucleon absorption KNN ! Yn

Bound region



Peak position

-130 MeV s

-90 MeV p

-50 MeV d

Simple Estimate of the Potential Depth

- Lowest Energy state
  - ~130 MeV bound
- Second Excited state
  - ~90 MeV bound
- Third
  - ~50 MeV (?)

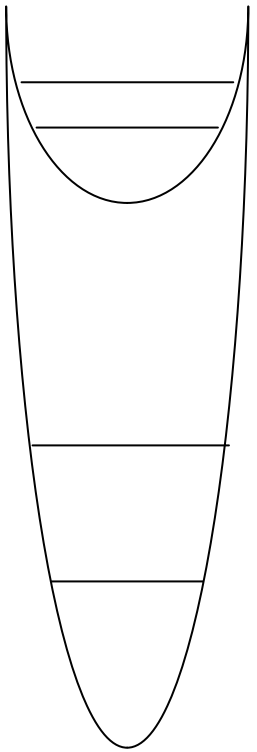
$$\hbar\omega \sim 40 MeV$$

$$BE \sim 130 MeV$$

$$-BE = U + 3/2\hbar\omega$$

$$U \sim -190 MeV$$

Shell Spacing



$$\hbar\omega_K \sim \hbar\omega_N \sqrt{V_K / V_N}\sqrt{m_N / m_K}$$

$$\hbar\omega_N \sim 15 MeV$$

$$\sqrt{V_K / V_N} \sim \sqrt{190/50}$$

$$\sqrt{m_N / m_K} \sim \sqrt{0.94/0.5}$$

$$\hbar\omega_K \sim 40 MeV$$

U~190 MeV

Decay Modes I

- Konic Nuclei ~ Λ(1405)
- I=0, J^{π}=1/2^{-}
- $\Lambda(1405)$ $\Rightarrow$

$\pi^{+}\Sigma^{-} \Rightarrow \pi^{-}$ n (1/3)

$\pi^{-}\Sigma^{+} \Rightarrow \pi^{+}$ n (1/6)

$\quad \Rightarrow \pi^{0}$ p (1/6)

$\pi^{0}\Sigma^{0} \Rightarrow \gamma\ \Lambda \Rightarrow \pi^{-}$ p (2/9)

$\quad \Rightarrow \pi^{0}$ n (1/9)

$\pi^{+}\pi^{-}$

π^{-}

π^{-}

2 charged π 1/2

1 charged π 2/9

2 π^{0} 1/9

Charged particle track vertex

Decay Modes II

- BE>100 MeV
  - Λ(1405)! Σ π energetically forbidden
- KNN ! YN (N: p n, Y: Λ Σ^{+0-})

- Ge efficiency
  - GEANT simulation
    - all YN and Λ(1405) decay
  - Efficiency 10~13% (Br is not known)
  - 11% (30 % systematic error)

Cross Section $^{16}O(K^-,n)$

- Experimental value
  - GS(s) ~80 μb/sr (50% stat. 30% syst. error) 13-4=9
  - 1st(p) ~450 μb/sr (20% stat. 30% syst. error)
  - 2^{nd}(d) 0.5~1 mb/sr

- Calculation (TK PRL)

  ^{12}C gs 100(490) μb/sr (~50 μb/sr Gal et al.)

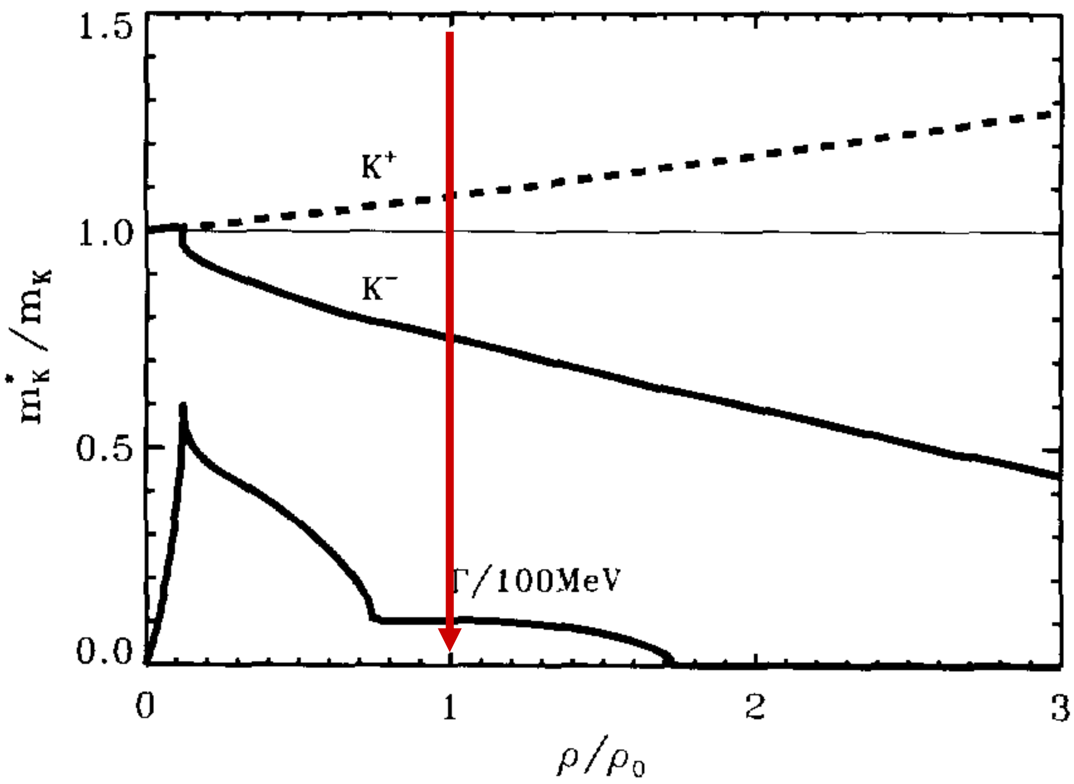
  ^{16}O gs 50~100 μb/sr

$\sigma_s : \sigma_p : \sigma_d = 1 : 6 : 7$

cross sections agree

Width

A little annoying



Observed width
Γ~26 MeV s(-130 MeV)
Γ~27 MeV p(-90 MeV)

Experimental resolution
37 MeV
TOF resolution ~120ps
(π Beam though)

Waas, Weise, PLB379(96)34

Γ could be ~ 10 MeV

1. Recoil proton (larger pulse height)
   better TOF res.
2. Statistics

Results

- States are seen @
  - -130, -90, -50 MeV
  - ~ ω ~ 40 MeV
- If lowest bound state is @ -130 MeV
  - All are consistent with U ~ 190 MeV
  - ~ω, Cross section
- Our spectrum is highly inconsistent with potential U ~ 40-80 MeV
- Our results show that potential depth is as deep as 200 MeV.

Current and future studies

- $^{12}C(K^-,p)$ E522
  - under analysis
- $^{16}O(K^-,p)$ excites I=1, though (K^-,n) I=0,1
  - I=0 (KN) pairs $\sum(1 - \tau_K \text{¢} \tau_N)/4$
  - 4.5 for I=0, 3.5 for I=1
  - $^{16}O(K^-,p)$: less deep potential ! Experiment

- Future J-PARC
  - Day 1 experiment
- Many interesting future experiment